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ENVELOPE IONIZATION MECHANISMS AND BW VULPECULAE

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ABSTRACT

Envelope ionization variations during the pulsations of β Cephei variables are known to be insufficient to drive pulsations in these stars in the presence of strong deeper radiative damping. If a model can be found with smaller than normal damping, or larger than normal helium ionization driving, then any intermittent core region driving will be more effective and will drive the pulsations to a larger than normal amplitude. If the net damping is so small then the decay of these pulsations will also be slower than normal. It is suggested that increased envelope helium, which might occur by accretion of matter from an evolved companion, or as just self homogenization, gives some helium ionization driving and a smaller decay rate. Perhaps BW Vulpeculae has such helium enriched surface layers which explain its unique large amplitude, even though the helium lines do appear normal.

I. BASIC DATA FOR BW VULPECULAE

BW Vul is a unique β Cephei variable due to its large amplitude in light and radial velocity variations. While it does show amplitude variations (Cherewick and Young 1975), it may be that its decay time is longer than the two reasonably well known cases, α Vir (Lomb 1978) and 16 Lac (Jarzebowski et al 1979).

TABLE I

HOMOGENEOUS COMPOSITION BW VULPECULAE MODEL

11.5 $M_\odot$ 25,000 K 6.0×10^{37} erg/s
$Y = 0.48$ (Cox-Hodson VII) $Z = 0.02$
Central Inert Ball $q = 0.04$ $x = 0.11$ $L_r/L = 1.00$ $T = 21 \times 10^6$ K
Convective Core (Z_3H_o = 0.1[illegible]) $q = 0.45$ $X = 0.30$ $T = 1$[illegible] $\times 10^{[illegible]}$ K
Last Mass 8×10^{-3} g One optically thin zone outside photosphere radius 4.64×10^{11} cm
Mass Ratio 1.61 for 47 zones, 0.725 for 13 zones
F Period 0.202 d (0.201 d observed); 1H Period 0.13[illegible] d; 2H Period 0.13[illegible] d
F Mode Decay Rate - 2.1×10^{-3} Π_0

From observations of the luminosity and the surface effective temperature, it seems reasonable to model this star with 11.5 $M_\odot$, 25,000 K, and a luminosity of 6×10^{37} erg/s (1.5×10^4 $L_\odot$). We take the helium mass fraction (Y) to be 0.48, a value that is possibly not unreasonable to have accreted or a value resulting from self homogenization. Such a BW Vul model with the usual convective core ($Y = 0.48$ also) gives a period of 0.201 day exactly the observed period. None of the adiabatic nonradial periods, which we feel should have the same period to give the Odell (1981) polarization, have the F mode period and therefore this model is not perfect from this viewpoint.

The Watson (1971) abundance of helium for this star is $Y = 0.25 \pm 0.02$. One should probably not argue with this value, but it has been obtained for a T_e = 23400 K and a log g = 3.81. For higher T_e perhaps a significantly larger Y will be needed to match the observed neutral helium lines. At any rate our model should be considered an extreme one, calculated to minimize radiative damping and maximize the pulsation amplitude and decay time.

A better model with the F and f^2 periods almost equal and the composition profile normal is given in Table II. The decay rate is now five times faster giving a time scale of 5.5 years just as for α Vir.

TABLE II

INHOMOGENEOUS COMPOSITION BW VULPECULAE MODEL

11.5 $M_\odot$ 24200K 5.87×10^{37} erg/s

$Y_s = 0.28$ (Cox-Davis VI) $Y_c = 0.68$ (Stellingwerf fit) $Z = 0.02$ everywhere

Central Inert Ball $q = 0.05$ $x = 0.07$ $L_c/L = 0.89$ $T = 30 \times 10^7$ K

Convective Core Surface ($\ell/H_p = 0.1$) $q = 0.25$ $x = 0.14$ $T = 23 \times 10^7$ K

μ Gradient Shell Outer Surface $q = 0.39$ $x = 0.16$ $T = 16 \times 10^7$ K

Last Zone Mass 8×10^{23} g One optically thin zone outside photosphere radius 4.90×10^{11} cm.

Mass Ratio 1.61 for 47 zones 0.722 for 13 zones

F Mode Period 0.202 d f^2 Period 0.207 d p_1^2 Period 0.157 d

F Mode Decay Rate $-1.0 \times 10^{-4}/\Pi_0$

TABLE III

Search Parameters for β Cephei Variability

(no convective core)

$M/M_\odot$	T_e Range	L Range	Composition Used
5.0	22,000 - 32,000 K	7×10^{37}	King IIIa, Cox-Davis VI
10.0	16,000 - 26,000 K	$4 \times 10^{37} - 7 \times 10^{37}$	King IIIa, King IVa, King Va, Caste I, Caste III, Caste IV, Caste V, Cox-Davis II, Cox-Davis VI, Cox-Hodson II, Cox-Hodson V, Cox-Hodson VI, Cox-Hodson VII
14.0	22,000 - 26,000 K	7×10^{37}	Cox-Tabor I, Caste II, Cox-Davis VI, Cox-Hodson II, Cox-Hodson V, Cox-Hodson VI, Cox-Hodson VII
15.0	22,000 - 26,000 K	$5 \times 10^{37} - 10^{38}$	Kin Ia, Caste II, Caste III, Cox-Davis I Cox-Davis II
20.0	22,000 - 26,000 K	7×10^{37}	Cox-Davis VI

II. ENVELOPE IONIZATION MECHANISMS

Table III gives results of search made to excite pulsations in β Cephei variables. They add to the work of Davey (1973) who used homogeneous composition envelopes. Parameter ranges in M, T_e, L and composition are given. Even extreme compositions given in Table IV do not show any destabilization.

TABLE IV

Mixture Compositions

Name	X	Y	Z
Kippenhahn Ia	0.602	0.354	0.044
King IIIa	.60	.38	.02
King IVa	.70	.28	.02
King Va	.80	.18	.02
Castellani I	.8	.1	.1
Castellani II	.6	.3	.1
Castellani III	.4	.5	.1
Castellani IV	.2	.7	.1
Castellani V	.0	.9	.1
Cox-Tabor I	.5	.4	.1 (pure C)
Cox-Davis I	.602	.354	.044
Cox-Davis II	.602	.354	.044
Cox-Davis IV	.800	.199	.001
Cox-Davis VI	.70	.28	.02
Cox-Hodson II	.00	.98	.02
Cox-Hodson V	.30	.68	.02
Cox-Hodson VI	.40	.58	.02
Cox-Hodson VII	0.50	0.48	0.02

Table V shows some detailed composition structures investigated. Each of the 10 rows indicate a composition structure with the fixed $M = 14\ M_\odot$, $T_e = 24{,}000$ K, and $L = 7 \times 10^{37}$ erg/s. Of particular interest is the model in row 8 where there is helium enrichment of $Y = 0.60$ to a depth where $T = 7 \times 10^6$ K. While the model is still stable against pulsations as seen in the last column, and has a longer per[illegible] next to last column) than usually observed, it has a pulsation decay time [illegible] times longer than most β Cephei models.

TABLE V

$14\ M_\odot$ β Cephei Models

24,000 K

7×10^{37} erg/s

(no convective core)

X	Y	Z	T(K)	X	Y	Z	T(K)	X	Y	Z	Π_0(d)	$\eta_0(\Pi_0^{-1})$
0.70	0.28	0.02	10^5	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.237	-2.1×10^{-5}
0.70	0.20	0.10	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.226	-2.8×10^{-5}
0.50	0.48	0.02	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.248	-1.3×10^{-5}
0.50	0.40	0.10	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.237	-1.8×10^{-5}
0.40	0.40	0.20	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.238	-1.6×10^{-5}
0.38	0.60	0.02	2×10^5	0.40	0.58	0.02	2.06×10^5	0.42	0.56	0.02	0.237	-2.1×10^{-5}
0.30	0.60	0.10	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.248	-1.2×10^{-5}
0.30	0.60	0.10	7×10^6	0.70	0.28	0.02	2×10^7	0.06	0.90	0.04	0.335	-1.0×10^{-6}
0.23	0.75	0.02	2×10^5	0.26	0.72	0.02	2.06×10^5	0.26	0.90	0.04	0.238	-2.1×10^{-5}
0.23	0.75	0.02	10^6	0.60	0.30	0.10	2×10^7	0.06	0.90	0.04	0.265	$-4.7 \times 10^{-?}$ [illegible]

All compositions use the Stellingwerf fit.

Extreme boundary conditions which are an attempt to mock up mass loss are used for models described in Table VI. A reduction of the last mass zone to lighten the outer layers, or a reduction of the acceleration due to gravity, g, results in structure changes that seem to increase stability. We note that a nearly companion also gives more concentrated structures and increased pulsation stability.

III. THE BW VUL MODEL

As an extreme case we have constructed a homogeneous composition model using the Cox-Hodson VII mixture with $Y = 0.48$. This structure, in Table I may not be unusual because Conti (private communication) suggests that perhaps the Wolf-Rayet stars occasionally homogenize themselves to bring the observed CNO cycle products to the surface. It is possible also that slow turbulence decay in some cases may reach the outer mass which normally does not have any mixing. In that case the star homogenizes itself. We are not able to get any smaller decay rate and still match the observed BW Vul period unless we enrich the surface Y to more than the interior, a strongly unstable μ gradient.

TABLE VI

10 $M_\odot$ β Cephei Models

24,000 K

7×10^{37} erg/s

(no convective core)

Surface Condition	Composition	Π_0(d)	$\eta_0(\Pi^{-1})$
$M_{last}/2$	Cox-Davis VI	0.24	-6.2×10^{-4}
$M_{last}/4$	Cox-Davis VI	0.24	-6.2×10^{-4}
$M_{last}/8$	Cox-Davis VI	0.83^{+}	-3.0×10^{-2}
g x 0.8 to 25,000 K and x 0.9 to 40,000 K	King IIIa	0.78	-6.2×10^{-5}
g x 0.6 to 25,000 K and x 0.8 to 40,000 K	King IIIa	0.43*	-2.9×10^{-4}

\+ adiabatic period $0^d.25$

* adiabatic period $0^d.66$

The figure gives the work per zone to drive pulsations in the homogeneous model for the lowest order radial modes. As in all β Cephei variables, there is a net damping when considering envelope ionization mechanisms only. Each overtone decays 10 or more times faster than the next lower mode, giving the radial fundamental the longest life of 4.8×10^{4} periods or 26 years. One can see that there is some helium ionization driving by the Stellingwerf (1978) mechanism in zones 41-48 (centered on 150,000 K), but it clearly is overwhelmed by the deep damping as many others have found especially for high T_e.

If one wants to increase the decay time of a free oscillation for the high amplitude BW Vul variable β Cephei it is possible that the star is homogeneous and helium rich. Note that this model is certainly not unique or desirable, and a lower surface helium and higher core helium is more conventional. Indeed if intermittent core mixing causes the BW Vul pulsations there would have to be at least some larger core helium than for the envelope.

An explanation of the high amplitude of BW Vul with a conventional structure may be that there are simultaneously 2 modes F and F$^-$ at exactly the same period whose pulsation amplitudes reinforce each other in the driving.

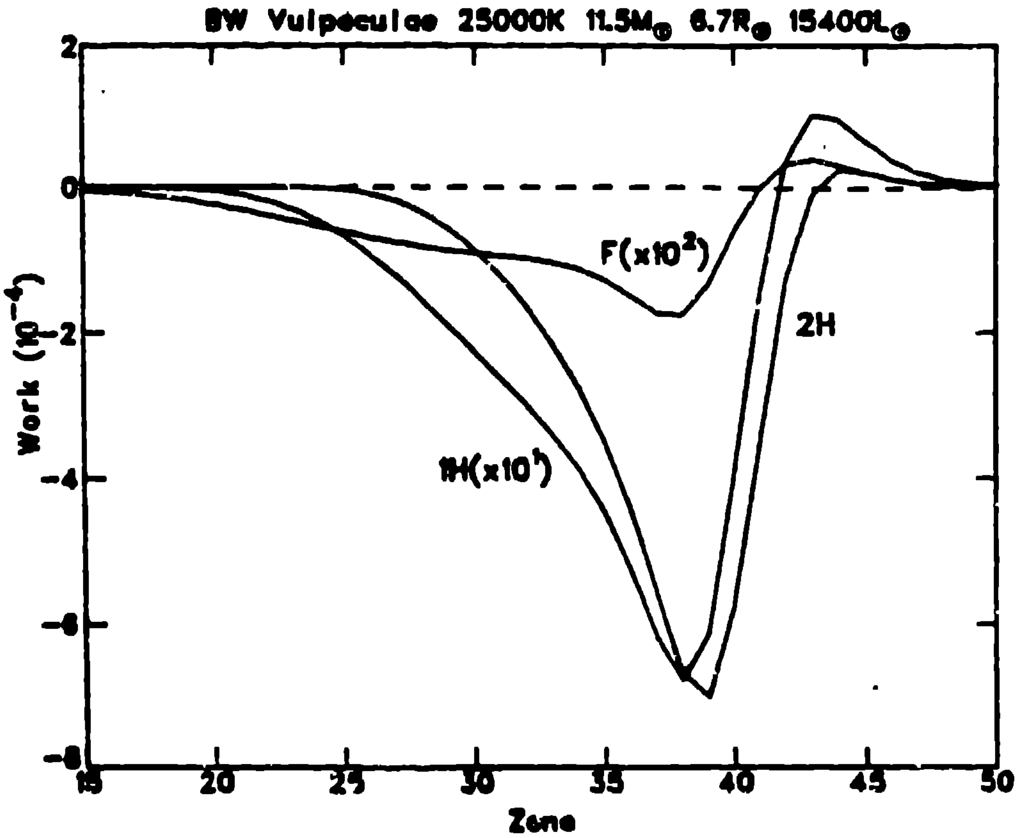

Figure 1. The work per zone to drive radial pulsations in the inhomogeneous BW Vul model. For this figure the Stellingwerf (1975) fit for the equation of state and opacity has been used to make the curves smoother. The F curve has been multiplied by 10^2 and the 1H by 10.

We note that the decay time of 20 years is not as long as observed in light amplitude (Percy 1980) which decays only 5 percent in 30 years giving an e-folding time of 580 years. It appears that BW Vul, and all β Cephei variables, have occasional core mixing episodes which cause temporary driving of the pulsations and these may occur when the previous excitation is still decaying. A look at the detailed amplitude history of BW Vul shows both increases and decreases on our predicted time scales. (Eggen 1948 and Cherewick and Young 1975).

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